# DOWNLINK SITE DIVERSITY WITH FREQUENCY-DOMAIN EQUALIZATION FOR A DS-CDMA CELLULAR SYSTEM

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## ABSTRACT

In DS-CDMA high speed wireless signal transmissions, the bit error rate (BER) performance with coherent rake combining degrades due to inter-path interference (IPI) caused by a severe frequency-selective fading. The use of frequency-domain equalization (FDE) can significantly improve the BER performance. However, the local average received signal power slowly varies due to path loss and shadowing loss according to the movement of a mobile user. This variation degrades the link capacity particularly when the user is located close to the cell edge. To improve the link capacity, the well-known site diversity can be used in conjunction with FDE. In this paper, we present downlink site diversity with FDE for a DS-CDMA cellular system and derive the MMSE weight for site diversity combining. The downlink capacity is evaluated by computer simulation and compared to the case with coherent rake combining. Then it is shown that the link capacity with FDE is better than that with coherent rake combining.

## 1. INTRODUCTION

Direct sequence code division multiple access (DS-CDMA) with coherent rake combining is used in third generation (3G) mobile communication systems that provide data services of up to a few Mbps [1]. In coherent rake receivers, the replicas of the transmitted signal propagated through different paths are resolved and coherently combined to obtain the path diversity gain. Recently, there have been tremendous demands for extremely higher speed data services than 3G systems [2]. The forth generation (4G) mobile communication systems are expected to emerge around 2010 or later. In 4G systems, 100Mbps~1Gbps class data transmission technology is said to be necessary. However, since the channel becomes severely frequency-selective [3], the bit error rate (BER) performance of DS-CDMA with coherent rake combining significantly degrades due to severe large inter-path interference (IPI). Recently, it was shown [4,5] that replacing the coherent rake combining with frequency-domain equalization based on minimum mean square error criterion (called MMSE-FDE) can significantly improve the BER performance of DS-CDMA.

However, in a cellular mobile communication system, as a mobile user moves, the local average received signal power slowly varies in time due to distance-dependent path loss and shadowing loss [3]. The performance degradation is severe when the mobile station (MS) is located close to the cell edge where the received signal power is weak and the interference from other cells is strong. Since the same carrier frequency can be used in a DS-CDMA cellular system, sufficient signal power can be obtained by transmitting the same signal simultaneously from different base stations (BS's) surrounding the MS [6]. This technique is called site diversity.

In this paper, we present downlink site diversity with MMSE-FDE for a DS-CDMA cellular system and derive the MMSE weight for site diversity combining. The downlink capacity is evaluated by computer simulation and compared to downlink capacity of coherent rake combining. The remainder of this paper is organized as follows. Section 1 presents the transmission system model of the downlink site diversity with FDE. In Section 3, the MMSE weight is derived. Section 4 presents the simulation results. Section 5 concludes this paper.

## 2. DOWNLINK DS-CDMA WITH SITE DIVERSITY AND FDE

### 2.1. Site diversity model

Figure 1 shows downlink site diversity model. In the downlink site diversity, as the number of base stations (active BS's) participating in site diversity increases, a larger interference is produced and degrades the downlink capacity. Hence, the selection method of active BS's is important. Firstly, assuming that all BS's are transmitting their pilot signals with equal power, an MS measures the local average received signal powers from surrounding BS's and sorts out them in descending order. The selection for active BS's is performed based on a threshold $P_{\rm th}$dB. A BS having a local average received signal power within the threshold from the maximum power will be selected as an active BS. All active BS's

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transmit the same signal simultaneously to the MS. If $P_{\mathrm{th}}$=0dB, MS communicates with only one BS having the maximum local average received signal power. The radio network controller (RNC) monitors the whole site diversity operation [7].

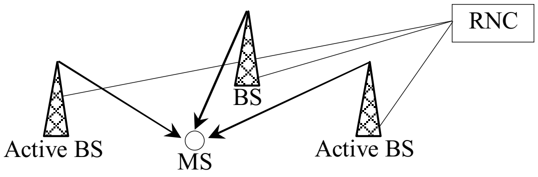


Fig.1 Downlink site diversity model.

### 2.2. Transmission system model

Figure 2 shows the BS transmitter/MS receiver structure. An active BS transmitting to the MS $u$ is denoted by BS $b(u)$. The maximum number of active BS's is limited to $D_{\max}$.

*2.2.1. Transmit signal representation*

Assume that BS $i$ is communicating with $U_i$ users. A binary data sequence to MS $u$ is transformed into a data symbol sequence $\{d_u(n);u=0\sim U_i-1\}$ respectively, and the data symbol sequence is divided into blocks composed of $N_c/SF$ symbols each, where $SF$ is the spreading factor and $N_c$ is the block size (in chips) for fast Fourier transform (FFT) at a mobile receiver. $SF$ is chosen so that the value of $N_c/SF$ becomes an integer. Figure 3 illustrates the block structure. In this paper, we consider the transmission of one block without loss of generality. After $U_i$ data symbol sequences $\{d_u(n);n=0\sim N_c-1\}$ are spread by orthogonal spreading codes $\{c_u(t);t=0\sim SF-1,\ u=0\sim U_i-1\}$, they are code multiplexed and then multiplied by a BS-specific scrambling code $\{c_{scr(i)}(t);t=0\sim N_c-1\}$. The last $N_g$ chips of the $N_c$-chip block is copied and inserted into the guard interval (GI) placed at the beginning of the block as a cyclic prefix. The equivalent lowpass representation $\tilde{s}_i(t)$ of the downlink signal from BS $i$ can be expressed as

$$\tilde{s}_i(t)=\sqrt{\frac{2E_c}{T_c}}s_i(t), \tag{1}$$

where $E_c$ is the chip energy per parallel data stream, $T_c$ is the chip duration and

$$s_i(t)=\left[\sum_{u=0}^{U_i-1}d_u\left(\lfloor t/SF\rfloor\right)c_u\left(t \bmod SF\right)\right]c_{scr(i)}(t), \tag{2}$$

where $\lfloor x\rfloor$ represents the largest integer smaller than or equal to $x$.

*2.2.2. Received signal representation*

The transmitted signal is received at MS $u$ via a frequency-selective fading channel with $L$ independent propagation paths. The impulse response $h_{i\_u}(t)$ of the multipath channel between BS $i$ and MS $u$ can be expressed as [8]

$$h_{i\_u}(t)=\sum_{l=0}^{L-1}h_{i\_u,l}\delta(t-\tau_l), \tag{3}$$

where $\{h_{i\_u,l};l=0\sim L-1\}$ is the $l$th path gain with $\sum_{l=0}^{L-1}E[|h_{i\_u,l}(t)|^2]=1$ ($E[.]$ denotes the ensemble average) and $\tau_l$ is $T_c$-spaced time delay of $l$th path. The received signal $r_u(t)$ at MS $u$ is given by

$$r_u(t)=\sum_{i=0}^{\infty}\sqrt{\frac{2E_{c,i\_u}}{T_c}}\left[\sum_{l=0}^{L-1}h_{i\_u,l}s_i(t-\tau_l)\right]+\eta(t), \tag{4}$$

where $E_{c,i\_u}$ is the local average received chip energy when the transmitted signal from BS $i$ is received at MS $u$ and expressed as

$$E_{c,i\_u}=E_c\cdot R_{i\_u}^{-\alpha}\cdot 10^{-\delta_{i\_u}/10}, \tag{5}$$

where $R_{i\_u}$ is the distance between BS $i$ and MS $u$, $\alpha$ is the path loss exponent, $\delta_{i\_u}$ is the log-normally distributed shadowing loss. $\eta(t)$ is the zero mean additive white Gauss noise (AWGN) process with variance $2N_0/T_c$ ($N_0$ is the single-sided power spectrum density) .

*2.2.3. Site diversity combining with FDE*

At MS $u$, after the removal of the GI, the received signal is decomposed into $N_c$ subcarrier components by $N_c$-point FFT. The $k$th subcarrier component $R_u(k)$ is given by

$$\begin{aligned}R_u(k)&=\sum_{t=0}^{N_c-1}r_u(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\&=\sum_{i=0}^{\infty}\left[\sqrt{\frac{2E_{c,i\_u}}{T_c}}H_{i\_u}(k)S_i(k)\right]+\Pi(k),\end{aligned} \tag{6}$$

where $S_i(k)$ is the $k$th subcarrier component of $s_i(t)$, $H_{i\_u}(k)$ is the $k$th subcarrier channel gain in the multipath channel between BS $i$ and MS $u$ and $\Pi(k)$ is the $k$th subcarrier component of $\eta(t)$. They are written as

$$\begin{cases}S_i(k)=\displaystyle\sum_{t=0}^{N_c-1}s_i(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\H_{i\_u}(k)=\displaystyle\sum_{l=0}^{L-1}h_{i\_u,l}\exp\left(-j2\pi k\frac{\tau_l}{N_c}\right)\\\Pi(k)=\displaystyle\sum_{t=0}^{N_c-1}\eta(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases}, \tag{7}$$

FDE is applied to $R_u(k)$ as follows:

$$\hat{R}_{b(u)}(k) = R_u(k) w_{b(u)}(k), \tag{8}$$

where $w_{b(u)}(k)$ is the MMSE weight to be derived in Sect.3. After $N_c$-point inverse FFT (IFFT) is applied, we obtain the time-domain chip sequence $\hat{r}_{b(u)}(t)$ given by

$$\hat{r}_{b(u)}(t) = \frac{1}{N_c} \sum_{k=0}^{N_c-1} \hat{R}_{b(u)}(k) \exp\left( j2\pi k \frac{t}{N_c} \right). \tag{9}$$

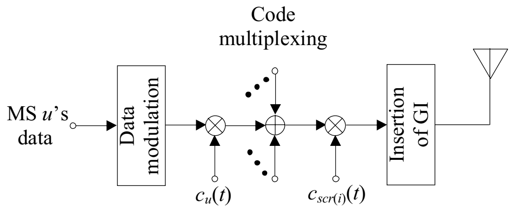
Then, despreading is carried out on $\hat{r}_{b(u)}(t)$ to get the decision variable $\hat{d}_{b(u)}(n)$ associated with the active BS $b(u)$ for transmitted symbol $d_u(n)$:

$$\hat{d}_{b(u)}(n) = \frac{1}{SF} \sum_{t=nSF}^{(n+1)SF-1} \hat{r}_{b(u)}(t) c^*_{scr(b(u))}(t) c^*_u(t \bmod SF). \tag{10}$$

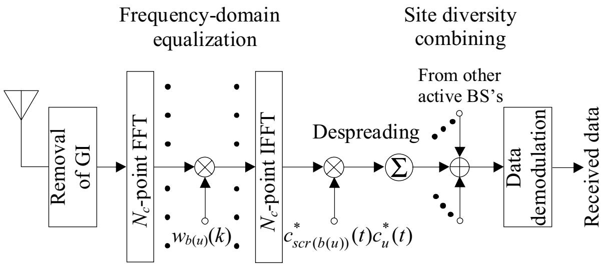
After despreading, by combining the decision variables associated with all active BS's (site diversity combining) , we obtain the soft decision sequence { $\tilde{d}_u(n)$ ;$n$=0~$N_c/SF-1$} . $\tilde{d}_u(n)$ is given by

$$\tilde{d}_u(n) = \sum_{b(u)=0}^{D-1} \hat{d}_{b(u)}(n), \tag{11}$$

where $D$ ($1 \leq D \leq D_{\max}$) is the number of active BS's. Finally, data demodulation is done to recover transmitted binary data sequence.



(a) Transmitter (BS $i$).



(b) Receiver (MS $u$).

Fig.2 Transmission system model.

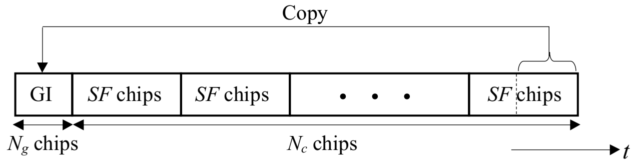


Fig.3 Block structure.

## 3. MMSE WEIGHT FOR SITE DIVERSITY WITH FDE

The MMSE weight for site diversity combining with FDE is derived assuming that $P_{\rm th} \rightarrow \infty$ and all BS's participate in site diversity ($D_{\max} \rightarrow \infty$) . Substituting Eq. (10) into Eq. (11) gives

$$\tilde{d}_u(n) = \frac{1}{SF} \sum_{t=nSF}^{(n+1)SF-1} \left[ \sum_{b(u)=0}^{\infty} \hat{r}_{b(u)}(t) \right] c^*_{scr(b(u))}(t) c^*_u(t \bmod SF). \tag{12}$$

The $k$th subcarrier component $\tilde{R}_u(k)$ of $\sum_{b(u)=0}^{\infty} \hat{r}_{b(u)}(t)$ is given by

$$\tilde{R}_u(k) = \sum_{b(u)=0}^{\infty} w_{b(u)}(k) \left[ \begin{array}{l} \displaystyle\sum_{i=0}^{\infty} \left( \sqrt{\frac{2E_{c,i\_u}}{T_c}} H_{i\_u}(k) S_i(k) \right) \\ +\Pi(k) \end{array} \right]. \tag{13}$$

The equalization error at the $k$th subcarrier is defined as

$$e_u(k) = \tilde{R}_u(k) - \tilde{S}_u(k), \tag{14}$$

where $\tilde{S}_u(k)$ is the $k$th subcarrier component in the sum of transmitted signals from all active BS's and it is written as

$$\tilde{S}_u(k) = \sum_{b(u)=0}^{\infty} \left[ \sqrt{\frac{2E_{c,b(u)\_u}}{T_c}} S_{b(u)}(k) \right], \tag{15}$$

where

$$\begin{aligned} S_{b(u)}(k) = & \sum_{t=0}^{N_c-1} \left[ d_u\left( \lfloor t/SF \rfloor \right) c_u\left( t \bmod SF \right) c_{scr(b(u))}(t) \right] \\ & \times \exp\left( -j2\pi k \frac{t}{N_c} \right). \end{aligned} \tag{16}$$

Using Eqs. (13), (14) and (15), the mean square error $E[|e_u(k)|^2]$ is given as

$$E\left[ |e_u(k)|^2 \right] = \sum_{b(u)=0}^{\infty} E\left[ \left| e_{b(u)}(k) \right|^2 \right], \tag{17}$$

where

$$
\begin{aligned}
&e_{b(u)}(k)\\
&= w_{b(u)}(k)\left[\sum_{i=0}^{\infty}\left(\sqrt{\frac{2E_{c,i\_u}}{T_c}}H_{i\_u}(k)S_i(k)\right)+\Pi(k)\right] \quad (18)\\
&\quad-\sqrt{\frac{2E_{c,b(u)\_u}}{T_c}}S_{b(u)}(k).
\end{aligned}
$$

The MMSE weight $w_{b(u)}(k)$ is found from

$$
\frac{\partial}{\partial w_{b(u)}(k)}E\left[\left|e_{b(u)}(k)\right|^2\right]=0. \quad (19)
$$

Substituting Eq. (18) into Eq. (19) gives [9]

$$
\begin{aligned}
&w_{b(u)}(k)\sum_{i=0}^{\infty}U_i\Gamma_{i\_u}\left|H_{i\_u}(k)\right|^2+SF\cdot w_{b(u)}(k)\\
&\qquad-\Gamma_{b(u)\_u}\left\{H_{b(u)\_u}(k)\right\}^*=0,
\end{aligned} \quad (20)
$$

where we have assumed that the data symbol sequences $\{d_u(n);u=0\sim U_i-1\}$ are independent and random variables. $\Gamma_{b(u)\_u}$ is the local average received signal energy per symbol-to-the AWGN power spectrum density ratio for the signal transmitted from BS $b(u)$ and is given by

$$
\Gamma_{b(u)\_u}=\frac{SF\cdot E_c(1+N_g/N_c)^{-1}}{N_0}R_{b(u)\_u}^{-\alpha}10^{-\delta_{b(u)\_u}/10}. \quad (21)
$$

From Eq. (20), the MMSE weight $w_{b(u)}(k)$ is obtained as

$$
w_{b(u)}(k)=\frac{\Gamma_{b(u)\_u}\left\{H_{b(u)\_u}(k)\right\}^*}{\sum_{i=0}^{\infty}U_i\Gamma_{i\_u}\left|H_{i\_u}(k)\right|^2+SF}. \quad (22)
$$

## 4. COMPUTER SIMULATION

We consider 19 hexagonal cells ($i$=0~18) and an MS of interest is located in the center cell ($i$=0th cell). We assume that each MS receives the signals from only 7 surrounding BS's and interference-limited environment. Table 1 shows simulation condition. The threshold $P_{\rm th}$ is set to $P_{\rm th}$=0~10dB, the required BER is set to $10^{-2}$ and the allowable outage probability $P_{\rm o}$ is set to $P_{\rm o}$=10%. We assume $D_{\max}$=7. Computer simulation is performed by the following procedure. Starting from $U$=1, $U$ MS's locations in each cell are randomly generated, followed by generation of shadowing loss $\delta_{i\_u}$ and path gains $\{h_{i\_u,l};l=0\sim L-1\}$. Each MS measures the local average received signal power from each BS to select active BS's, each having the local average received signal power within the threshold $P_{\rm th}$dB from the maximum. After selecting active BS's, the number $U_i$ of data channels of BS $i$ is determined. The BER measurement of the MS is carried out. After the measurement of the local average BER, the locations of all MS's are changed to measure the local average BER again. This measurement process is repeated a sufficient number of times to find the distribution of local average BER. If the probability (outage probability) of the local average BER being larger than the required BER is smaller than $P_{\rm o}$, the number $U$ of MS is incremented by one (i.e. $U+1\rightarrow U$). The downlink capacity $U_{\max}$ is defined as the maximum number of MS that keeps the outage probability smaller than $P_{\rm o}$.

Table 1 Simulation condition.

| | | |
|---|---|---|
| DS-CDMA Transmitter /Receiver | Data modulation | QPSK |
| | No. of FFT points | $N_c$=256 |
| | GI lengths | $N_g$=32 |
| | Spreading code | Walsh-Hadamard code |
| | Scrambling code | Long PN code |
| | Spreading factor | $SF$=256 |
| | Frequency-domain equalization | MMSE |
| | Channel estimation | Ideal |
| Site diversity | User distribution | Uniform |
| | Threshold | $P_{\rm th}$=0~10dB |
| | Maximum no. of active BS's | $D_{\max}$=7 |
| Link quality requirement | Required BER | $10^{-2}$ |
| | Allowable outage probability | $P_{\rm o}$=10% |
| Channel model | Path loss exponent | $\alpha$=3~4 |
| | Standard deviation of shadowing loss | $\sigma$=6(dB) |
| | Fading | Block Rayleigh fading |
| | No. of paths | $L$=16 |
| | Power delay profile | Uniform |

Figure 4 shows the normalized link capacity $U_{\max}/SF$ as a function of the threshold $P_{\rm th}$. As $P_{\rm th}$ increases, the normalized downlink capacity increases due to the increase in site diversity effect. However, when $P_{\rm th}$ exceeds a certain value, the normalized downlink capacity decreases because of the excessive interference due to the increase in the number of active BS's. The maximum downlink capacity is about 1.3 times larger than without site diversity ($P_{\rm th}$=0dB) . As the path loss exponent $\alpha$ increases, the optimum $P_{\rm th}$ that maximizes the downlink capacity increases. This is because $P_{\rm th}$ needs to be increased to get more active BS's for site diversity. The optimum $P_{\rm th}$ is found to be around 4~5dB when $\alpha$=3~4. It is also seen that the downlink capacity with MMSE-FDE is superior to that with coherent rake combining; the maximum downlink capacity with MMSE-FDE is about 1.6 times larger than with coherent rake combining. This is because MMSE-FDE can significantly reduce the IPI.

Figure 5 shows the probability of the number $D$ of active BS's when $\alpha$=3.5. As $P_{\rm th}$ increases, the probability of $D$=4~6 becomes larger. This suggests that the intercode interference is severer if $P_{th}$ is too large. When the optimum $P_{th}$ (4.5dB) is used, the sufficient signal power can be collected by site diversity and the excessive interference is avoided due to the small probability of $D$=4~7.

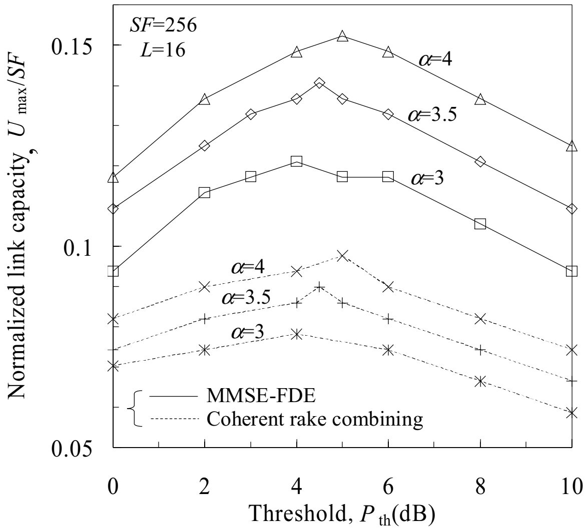


Fig.4 Effect of site diversity threshold $P_{th}$ on downlink capacity.

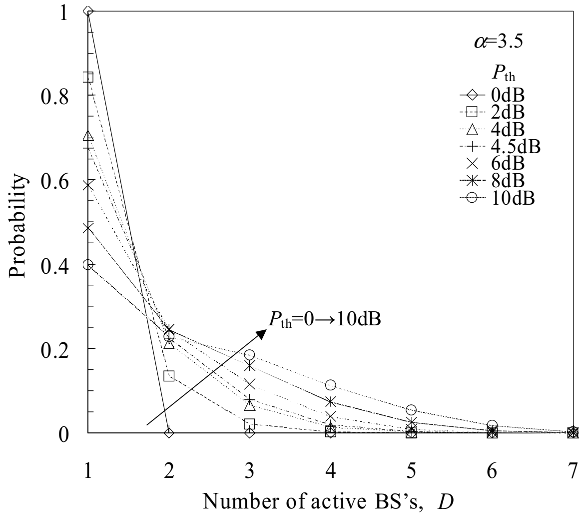


Fig.5 Probability of the number $D$ of active BS's.

## 5. CONCLUSION

In this paper, we presented the downlink site diversity with MMSE-FDE for a DS-CDMA cellular system and the MMSE weight for site diversity with FDE was derived. It was shown by computer simulation that the optimum threshold that maximizes the downlink capacity exists and the downlink capacity with site diversity is about 1.3 times larger than without site diversity. It was also shown that site diversity with MMSE-FDE is superior to site diversity with coherent rake combining; the maximum downlink capacity with MMSE-FDE is about 1.6 times larger than that with coherent rake combining.

## REFERENCES

[1] F. Adachi, M. Sawahashi, and H. Suda, "Wideband DS-CDMA for next generation mobile communications systems," IEEE Commun. Mag., Vol.36, pp.56-69, Sept. 1998.

[2] Y. Kim *et al*, "Beyond 3G: vision, requirements, and enabling technologies," IEEE Commun. Mag., Vol.41, pp.120-124, Mar. 2003.

[3] W. C. Jakes, Jr., Ed., *Microwave mobile communications*, Wiley, New York, 1974.

[4] D. Falconer, S. L. Ariyavistakul, A. Benyaminseeyar, and B. Eidson, "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., Vol.40, pp.58-66, Apr. 2002.

[5] F. Adachi, D. Garg, S. Takaoka, and K. Takeda, "Broadband CDMA techniques," IEEE Wireless Commun. Mag, Vol.12, No.2, pp.8-18, April. 2005.

[6] A. J. Viterbi, *CDMA*: *principles of spread spectrum communications*, Addison-Wesley, 1995.

[7] T. Ojanpera and R. Prasad, *Wideband CDMA for third generation mobile communications*, Artech house, 1998.

[8] T. S. Rappaport, *Wireless communications*, Prentic Hall, 1996.

[9] T. Inoue, S. Takaoka and F. Adachi, "Frequency-domain equalization for MC-CDMA downlink site diversity and performance evaluation," IEICE Trans. Commun., Vol.E88-B, No.1, pp.84-92, Jan. 2005.